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Shortening and Thickening of Metropolitan Los Angeles Measured and Inferred Using Geodesy

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ABSTRACT

Geodetic measurements using the Global Positioning System and other techniques show north-south shortening near Los Angeles to be fastest across the northern part of the metropolitan area, where an ESE-striking, 5- to 40-km-wide belt lying to the south of the San Gabriel Mountains and to the north of downtown and West Los Angeles is shortening at 5 mm/yr. Aside from elastic strain that will be released during earthquakes rupturing the San Andreas fault, east-west lengthening across metropolitan L.A. is minor. Therefore crustal thickening must be the main process taking up the north-south shortening.

Tectonic Setting of Metropolitan L.A.

Motion between the Pacific and North American plates is at a 30° convergent angle with the 160-km-long segment of the San Andreas fault adjacent to the Mojave Desert. This Big Bend in the San Andreas complicates the tectonic character of the area—the high mountains of the Eastern, Central, and Western Transverse Ranges and the intersection of the left-slipping Garlock fault with the right-slipping San Andreas are manifestations of the Big Bend. The rate of right shear parallel to the WNW-trending San Andreas fault is high (0.4×10^{-6}/yr) in the few tens of km nearest the fault (Lisowski and others 1991). Most if not all of this slip is elastic strain building up in response to locking of the San Andreas and will be recovered in great earthquakes similar to the 1857 M=8.2 Fort Tejon earthquake, which resulted in 3 to 9 m of right slip along 400 km of the San Andreas (Sieh and others 1978).

The Big Bend in the San Andreas also produces north-south shortening 50 km to the south of the fault, in and near metropolitan L.A. This shortening is evident in the rugged and youthful topography along the southern base of the San Gabriel Mountains (Yeats and others 1994), in the shortening of north-south distances across L.A. observed with geodesy (Feigl and others 1993), and in the reverse slip occurring during the 1971 M=6.6 San Fernando, 1987 M=5.8 Whittier, and 1992 M=6.7 Northridge earthquakes. Moderately large (M=6.5 to 7.4) earthquakes in metropolitan L.A. may cause as much damage as a very large (M=8.2) earthquake rupturing the more distant San Andreas (Dolan and others 1995).

Interseismic Velocity Field

We estimate the velocity of 200 sites in southern California using five sets of geodetic data: permanent Global Positioning System (GPS), campaign GPS, geodolite, Very Long Baseline Interferometry (VLBI), and Satellite Laser Ranging (SLR). Using data from January 1991 to May 1998, we estimate the velocity of 175 global permanent GPS sites using the GIPSY data reduction package. Plots showing position as a function of time for all 175 sites are available on the internet at http://sideshow.jpl.nasa.gov/mbh/series.html. Thirty-five of the 175 sites are part of the Southern California Integrated GPS Network (SCIGN), a dense array across metropolitan L.A. Thirty of the 35 SCIGN sites have 2.5 to 4 years of data, all of which are from after the 1994 Northridge earthquake. The remaining five sites are permanent GPS geodetic array (PGGA) sites and have data over 6 to 7 years (Bock and others 1997). The SCIGN data are the basis for the new results presented herein.

The campaign GPS velocity solution we incorporate (D. Dong, electronic comm. 1998) is from data from the Southern California Earthquake Center (SCEC) from June 1986 to 28 June 1992, the day of the M=7.1 Landers earthquake. (We omit SCEC campaign data from after the Landers earthquake to avoid postseismic transients.) The rates of change of line lengths among 155 trilateration marks measured with geodolite from 1970 to 1990 (U.S. Geological Survey, electronic comm. 1998) tightly constrains the kinematics of the area within a few tens of km of the San Andreas fault. Neither the SCEC campaign nor the geodolite data constrain the velocity of California sites relative to the interiors of the major plates. We therefore impose velocity ties to permanent GPS, VLBI, and SLR sites at 24 places to put the SCEC campaign and geodolite velocities into frames fixed to the plate interiors.

We aim to estimate an interseismic velocity field unbiased by either coseismic offsets or postseismic transients. Postseismic transients arising from the 1992 Landers and 1994 Northridge earthquakes do not bias the geodolite, SCEC campaign, VLBI, and, SLR data because nearly all these data are from before the Landers earthquake. Postseismic transients due to the Northridge earthquake are small but significant within a few tens of km of the rupture (Donnellan and Lyzenga 1998). But Northridge postseismic effects on the SCIGN velocities are likely small, mostly because the SCIGN data at of the sites nearest the rupture begin 0.5 to 2.25 years after the earthquake. Using the dislocation model of Donnellan and Lyzenga, and assuming that the characteristic time describing exponential decay of transients is 1 year, we estimate postseismic transients not yet dissipated at the start of data acquisition to be: 14 mm (AOA), 10 mm (Rocketdyne), 5 mm (Camp 9), 4 mm (Pacoima Dam 1), 4 mm (Saddle Peak), 4 mm (Oat Mountain), and minor elsewhere. The time evolution of positions at AOA and Rocketdyne show furthermore that postseismic effects at these two sites are small and rule out transients as large as predicted.

The east component of velocity of the permanent GPS site at JPL increased abruptly by ~15 mm/yr during the Northridge earthquake (Heflin and others 1998). The pre-Northridge GPS velocity is anomalous with regard to the pre-Landers VLBI velocity whereas the post-Northridge GPS velocity is consistent with the pre-Landers VLBI velocity. We take the post-Northridge GPS velocity to be representative of the interseismic velocity field and omit the anomalous pre-Northridge GPS data. The two decades of geodolite data exhibit, aside from coseismic offsets, only one variation in rate, supporting the idea that the interseismic velocity field is nearly constant aside from coseismic offsets and postseismic transients (Savage and Lisowski 1995). On the other hand Jackson and others (1997) and Savage and Lisowski (1998) suggest that the interseismic velocity varies over several decades.

Elastic Strain Due to Locking of the San Andreas Fault

We aim to determine the strain that is being or will be released in and near metropolitan L.A. Therefore we remove from the velocity field the elastic strain that is building up due to locking of the San Andreas and San Jacinto faults. We approximate this elastic strain using a model consisting of screw dislocations along the locked segments of the two faults. We assume fault segments are locked from the surface to the maximum depth of seismicity, which is 13 to 20 km (Hill and others 1990; Magistrale and Zhou 1996). We assume also that fault segments are accumulating slip deficits at rates equal to Holocene slip rates estimated from paleoseismology (WGCEP 1995).

Geodolite data exhibit a more gentle gradient in the component of velocity parallel to the Mojave segment of the San Andreas than would be expected from a 15-km locking depth and a 30-mm/yr slip rate (Eberhart-Phillips and others 1990; Lisowski and others 1991; Shen and others 1996; Savage and others 1998). Therefore, rather than using the numbers from seismicity and paleoseismology, we estimate the locking depth and slip rate deficit using the geodetic data. We assume that the crust on either side of the fault is comprised of two distinct crustal blocks, the west Mojave Desert block to the northeast and the San Gabriel Mountains block to the southwest. We assume also that all strain in the two blocks is elastic strain due to locking of the San Andreas and San Jacinto faults, and that all this elastic strain will be recovered in right-slip earthquakes breaking the two faults. The western Mojave Desert block is bounded on the southwest by the San Andreas fault, on the northwest by the Garlock fault, and on the east by the eastern California shear zone. One VLBI, one SCEC campaign, two permanent GPS, and 14 geodolite sites are on the west Mojave Desert block. The San Gabriel Mountains block is bounded on the northeast by the San Andreas fault, on the south by the San Fernando-Sierra Madre-Cucamonga fault, and on the west by the San Gabriel fault. Two permanent GPS and 17 geodolite sites are on the San Gabriel Mountains block. (We also impose the requirement that the component of the velocity between the two crustal blocks that is parallel to the fault segment be equal to the slip rate deficit. This requirement is implicit in the assumption that the fault is locked.) We next use trial and error to find the locking depth and slip rate that minimizes data misfits assuming the two crustal blocks are rigid aside from the elastic strain due to locking of the two faults. We find the best-fitting parameters to be a locking depth of 20 ±3 km and a slip rate of 25 ±3 mm/yr. The parameter estimates are from a joint inversion of all the geodetic data and a single geologic datum, the 30 ±5 mm/yr Holocene slip rate for the Mojave fault segment from paleoseismology. The best-fitting parameters from the geodetic data alone are 18 km and 23 mm/yr. The two parameters covary, with deeper locking depths corresponding to faster slip rates.

The data show that, aside from the elastic strain due to locking of the San Andreas, the two blocks are indeed behaving nearly rigidly. The weighted root mean square of residuals for the San Gabriel Mountains block is 0.54 mm/yr and that for the west Mojave Desert block is 0.66 mm/yr. Therefore it appears likely that nearly all the strain building up in the two blocks is elastic and will be recovered in right-slip earthquakes along the San Andreas. It is unsurprising that the data misfits are small in the western Mojave Desert block because few earthquakes and only minor faults occur therein. One might suspect that north-south shortening across the San Gabriel Mountains block might be presently building the ranges, but the data require shortening perpendicular to the San Andreas to be about zero (Lisowski and others 1991).

North-South Shortening Across Northern Metropolitan Los Angeles

In Figure 1 we show the velocity field after removing the elastic strain due to locking of the San Andreas and San Jacinto faults. Six sites on four Channel Islands are fixed. Figure 2 shows the south component of the velocity field along four north-south profiles, whereas Figure 3 shows the west component of the velocity field. The velocity field provides a description of the strain that is being or will be released in and near metropolitan L.A.

Relative to the Channel islands the San Gabriel Mountains are rotating clockwise about a pole of rotation (34.4°N, 122.5°W) 3.5°/Myr. due west of Los Angeles. The eastern part of the San Gabriel Mountains block is moving due south at 8 ±2.5 mm/yr relative to the Channel islands, whereas the western part of the block is moving due south at 9.5 ±4 mm/yr (Figure 1). (95% confidence limits are quoted after the "±" here and everywhere in this article.) North-south shortening must be occurring between the Mountains and the islands. The north-south shortening is perpendicular to the trend of the central Transverse Ranges, suggesting that the mountains rose over the past several million years in a tectonic regime not unlike that of the present day.

The data show that ~5 mm/yr of the north-south shortening is being taken up across an east-southeast-trending, 5- to 40-km-wide belt crossing the northern part of metropolitan L.A. (Figures 1 and 2). In the west north-south shortening at 6 mm/yr is occurring across the narrow Ventura basin, which is bounded on the north by the San Cayetano thrust and on the south by the Oak Ridge fault. The belt is bounded on the north by Hopper and Santa Paula 2 and on the south by Happy Camp. Santa Paula lies inside the belt. The 6 mm/yr of shortening we find is near the lower limit of the 7 to 10 mm/yr of Donnellan and others (1993ab). The shortening is occurring across a belt just 5 km wide, making the contractional strain rate exceptionally high (1.2×10^{-6}/year). The crust south of the Ventura basin from the Oak Ridge Mountains to the Santa Monica Mountains appears to be behaving rigidly (Donnellan and others 1993ab) aside from the elastic strain due to locking of the San Andreas. That is, Happy Camp, Rocketdyne, AOA, Castro peak, Saddle peak, and UCLA appear to be on an elastic block.

To the east the data confine the belt to a 40-km-wide area bounded on the north by Loma Verde, Camp 9, and Pacoima Dam 1 and on the south by Rocketdyne and UCLA. Shortening may be being accommodated in the Santa Clarita Valley, in the Santa Susana Mountains, and in the San Fernando Valley. The north-south shortening is roughly parallel to the horizontal projection of the reverse slip that occurred during the 1994 M=6.7 Northridge (USGS and SCEC 1994) and the 1971 M=6.6 San Fernando earthquakes. The 6.7 Northridge earthquake ruptured the Santa Susana fault, a south-dipping thrust inside the shortening belt. The San Fernando earthquake ruptured the San Fernando and Sierra Madre faults, two adjacent thrusts that dip north at ~45° beneath the sites at Camp 9 and Pacoima Dam 1.

Near Pasadena the data confine the belt to lie to the north of UCLA and USC and to the south of the Sierra Madre thrust, which divides the San Gabriel Mountains from the valleys south of it. Shortening at ~5 mm/yr is occurring across the 30-km-wide belt. Geologic evidence for north-south shortening include reverse and right slip along the Verdugo fault, which bounds the steep southern face of the Verdugo and San Rafeal hills; reverse slip along the Hollywood fault, which bounds the Beverly and Hollywood hills on the south; left slip along the Raymond fault, which cuts across Pasadena; reverse slip and right slip across the Whittier fault; and the Elysian Park anticline, which lies above the blind Elysian Park thrust [Davis et al. 1989]. The similarity of the height and roughness of the Verdugo Hills with that of the San Gabriel Mountains make it appear that the Hills are becoming part of the Mountains as the valley between them closes. The north-south shortening is roughly parallel to the direction of reverse slip occurring during the 1987 M=5.8 Whittier Narrows earthquake.

Shortening across the belt may decrease slightly going eastward from USC, as it appears only ~4 mm/yr of north-south shortening is being taken up north of Whittier College. Farther east the data indicate north-south shortening is distributed roughly evenly across a wide area between the eastern San Gabriel Mountains and the Channel islands. North-south shortening appears to be occurring at 4 mm/yr north of the Santa Ana Mountains at at 5 mm/yr south of the Santa Ana Mountains. The geodolite data indicate that right slip across the Elsinore fault is occurring at only a couple mm/yr (Lisowski and others 1991), near the low end of the 5 ±2 mm/yr Holocene slip rate from the WGCEP (1995).

Lack of Elastic Strain Along the Sierra Madre-Cucamonga Thrust

If the Sierra Madre-Cucamonga thrust were presently building up elastic strain at, say, 5 mm/yr, we would expect the southern part of the San Gabriel Mountains to be contracting at few mm/yr. The data show no contraction there at all. The 1971 San Fernando earthquake ruptured the thrust, indicating that there is some elastic strain building up along the fault. The observation of no contraction in the southern San

Gabriel Mountains is nevertheless consistent with the minor Holocene slip rates inferred from paleoseismology. Rubin and others (1998) postulate that 2 M=7.4 earthquakes rupturing the Sierra Madre thrust near Pasadena over the past 15,000 years accompanied 10.5 m of reverse slip, yielding a slip rate of 0.7 mm/yr. Walls and others (1998) estimate Holocene slip rates of 2 +1/−0.5 mm/yr for the western Sierra Madre thrust, 1 ±0.5 mm/yr for the central Sierra Madre thrust, and 3 ±1 mm/yr for the Cucamonga thrust. The data therefore indicate that the present locus of north-south shortening is south of the Sierra Madre-Cucamonga thrust.

Lack of East-West Lengthening Across Metropolitan L.A.

Walls and others (1998) maintain that the metropolitan L.A. area is undergoing east-west lengthening in response to north-south shortening. They estimate the east-west lengthening rate to be 6 mm/yr. We, in contrast, find the lengthening rate to be 0 ±2.5 mm/yr (Figure 3). Nearly half of the difference between them and us is due to our removal of the elastic strain due to locking of the San Andreas and San Jacinto faults. This elastic strain removal reduces the east-west lengthening between Palos Verdes and Lake Mathews, which are the two sites on either end of their study area, by 2.8 mm/yr. Thus earthquakes rupturing the San Andreas fault similar to the 1857 earthquake will result in east-west shortening across metropolitan L.A., thus recovering east-west lengthening building up over the interseismic period.

An additional one-quarter of the difference between us and Walls and others is due, we believe, to overstatement on their part. From Figure 2 of Walls and others we estimate that the east component of velocity differs between Lake Mathews and Palos Verdes by 4.5 mm/yr, which is 1.5 mm/yr less than the 6 mm/yr they quote on page 359. The remaining difference, which is 1.7 mm/yr, is due to differences between the geodolite results, which we use and they don't, and the permanent GPS results.

Whereas the geodolite data indicate that strike slip along the Elsinore fault is minor, the GPS data from Tracker and Lake Mathews suggest that the Elsinore fault is slipping right-laterally at 3.8 mm/yr south of its junction with the Whittier fault, which would produce 2.6 mm/yr of east-west extension across the fault southeast of L.A.

If metropolitan L.A. is not undergoing significant east-west lengthening then it must be thickening. The conclusion that crustal thickening is the main process accommodating north-south shortening supports Davis and others' (1989) interpretation of the structure beneath L.A. as being a fold and thrust belt. The geodetic estimate of the shortening rate between Palos Verdes and the San Gabriel Mountains block is 5.8 ±1.9 mm/yr, which is consistent with the 3.8 to 6.8 mm/yr minimum convergence rate since 2.2 to 4 Ma estimated by Davis and others (1989). The conjugate faulting evident in strike slip along the Verdugo, Raymond, San Jose, Chino, and Whittier faults is also taking up some of the north-south shortening, but the slow slip rates estimated by Walls and others (1998) indicate that strike slip and east-west lengthening is playing less of a role than reverse slip and thickening. Similarly, the largest historical earthquakes in the area, the 1971, 1987, and 1994 earthquakes, produced far less strike slip and east-west extension than dip slip and vertical thickening. The locus of present-day mountain building appears to have shifted over to the south the past few million years, away from the San Gabriel Mountains to northern metropolitan L.A.

References Cited

Bock, Y., Wdowinski, S., Fang, P., Zhang, J., Williams, S., Johnson, H., Behr, J., Genrich, J., Dean, J., van Domselaar, M., Agnew, D., Wyatt, F., Stark, K., Oral, B., Hudnut, K., King, R., Herring, T., Dinardo, S., Young, W., Jackson, D., and Gurtner, W., 1997, Southern California Permanent GPS Geodetic Array: Continuous measurements of regional crustal deformation between the 1992 Landers and 1994 Northridge earthquakes: Journal of Geophysical Research, v. 102, p. 18,013-18,033.

Davis, T. L., Namson, J., and Yerkes, R. F., 1989, A cross section of the Los Angeles area: Seismically active fold and thrust belt, the 1987 Whittier Narrows earthquake, and earthquake hazard: Journal of Geophysical Research, v. 94, p. 9644-9664.

Dolan, J. F., Sieh, K., Rockwell, T. K., Yeats, R. S., Shaw, J., Suppe, J., Huftile, G. J., and Gath, E. M., 1995, Prospects for larger or more frequent earthquakes in the Los Angeles metropolitan region: Science, v. 267, p. 199-205.

Donnellan, A., Hager, B. H., and King, R. W., 1993a, Discrepancy between geological and geodetic deformation rates in the Ventura Basin: Nature, v. 366, p. 333-336.

Donnellan, A., Hager, B. H., King, R. W., and Herring, T. A., 1993b, Geodetic measurement of deformation in the Ventura basin region, southern California: Journal of Geophysical Research, v. 98, p. 21,727-21,739.

Donnellan, A., and Lyzenga, G. A., 1998, GPS observations of fault afterslip and upper crustal deformation following the Northridge earthquake: Journal of Geophysical Research, v. 103, p. 21,285-21,297.

Eberhart-Phillips, D., Lisowski, M., and Zoback, M. D., 1990, Crustal strain near the big bend of the San Andreas fault: Analysis of the Los Padres-Tehachapi trilateration networks, California: Journal of Geophysical Research, v. 95, p. 1139-1153.

Feigl, K. L., Agnew, D. C., Bock, Y., Dong, D., Donnellan, A., Hager, B. H., Herring, T. A., Jackson, D. D., Jordan, T. H., King, R. W., Larsen, S., Larson, K. M., Murray, M. M., Shen, Z., and Webb, F. H., 1993, Space geodetic measurement of the velocity field in central and southern California, 1984-1992: Journal of Geophysical Research, v. 98, p. 21,677-21,712.

Heflin, M., Dong, D., Donnellan, A., Hurst, K., Jefferson, D., Watkins, M., Webb, F., Zumberge, J., Dauger, D., and Lyzenga, G., 1998, Rate change observed at JPLM after the Northridge earthquake: Geophysical Research Letters, v. 25, p. 93-96.

Hill, D. P., Eaton, J. P., and Jones, L. M., 1990, Seismicity, 1980-86: *in* R. E. Wallace, ed., The San Andreas Fault System, California: USGS Professional Paper 1515, p. 115-151.

Jackson, D. D., Shen, Z.-K., Potter, D., Ge, X.-B., and Sung, L.-Y., 1997, Southern California Deformation: Science, v. 277, p. 1621-1622.

Lisowski, M., Savage, J. C., and Prescott, W. H., 1991, The velocity field along the San Andreas fault in central and southern California: Journal of Geophysical Research, v. 96, p. 8369-8389.

Magistrale, H., and Zhou, H., 1996, Lithologic control of the depth of earthquakes in southern California: Science, v. 273, p. 639-642.

Savage, J. C., and Lisowski, M., 1995, Interseismic deformation along the San Andreas fault in southern California: Journal of Geophysical Research, v. 100, p. 12,703-12,717.

——, 1998, Viscoelastic coupling model of the San Andreas fault along the big bend, southern California: Journal of Geophysical Research, v. 103, p. 7281-7292.

Shen, Z.-K., Jackson, D. D., and Ge, B. X., 1996, Crustal deformation across and beyond the Los Angeles basin from geodetic measurements: Journal of Geophysical Research, v. 101, p. 27,957-27,980.

Sieh, K. E., 1978, Slip along the San Andreas Fault associated with the great 1857 earthquake: Bulletin of the Seismological Society of America , v. 68, p. 1421-1448.

U.S. Geological Survey the Southern California Earthquake Center, Scientists of, 1994, The magnitude 6.7 Northridge, California, Earthquake of 17 January 1994: Science, v. 266, p. 389-397.

Walls, C., Rockwell, T., Mueller, K., Bock, Y., Williams, S., Pfanner, J., Dolan, J., and Feng, P., 1998, Escape tectonics in the Los Angeles metropolitan region and implications for seismic risk: Nature, v. 394, p. 356-360.

Working Group on California Earthquake Probabilities, 1995, Seismic hazards in southern California: Probable Earthquakes, 1994 to 2024: Bulletin of the Seismological Society of America , v. 85, p. 379-439.

Yeats, R. S., Huftile, G. J., and Stitt, L. T., 1994, Late Cenozoic tectonics of the east Ventura basin, Transverse ranges, California: American Association of Petroleum Geologists Bulletin, v. 78, p. 1040-1074.

Figure Captions

Figure 1. The velocity field after removing the elastic strain due to locking of the San Andreas and San Jacinto faults. The Channel Islands are fixed. The velocity of the Channel Islands block is estimated using six sites on Catalina, San Clemente, San Nicholas, and Santa Cruz Islands. Speeds are given in mm/yr. North-south shortening is fastest across the belt marked by the magenta-dashed lines. The site speeds decrease quickly by ~5 mm/yr going from north to south across this belt. Fault plane solutions are shown for the 1971 San Fernando, 1987 Whittier Narrows, and 1994 Northridge earthquakes. Equal-area projections of the lower hemisphere of the focal sphere are plotted; the black quadrants correspond to compressional first motion. The horizontal projections of the fault slip planes are plotted as open white rectangles. The one-dimensional standard error in the velocity of a permanent GPS site, which we estimate using both the degree of consistency among techniques and with plate rigidity, ranges from 1.2 to 2.0 mm/yr. The velocity of the permanent GPS site at Hollydale is unreliable because there is an unexplained break in the time series and because there is a large drift in the phase residuals with time. The four north-south profiles shown in Figure 2 are divided by black-dashed lines. Site abbreviations are: (AOA) Allen Osborne Associates, (BB) Brand Basin, (CF) Chileo Flats, (CIT) California Institute of Technology, (CP) Castro Peak, (Cp9) Camp 9, (CSN) California State University at

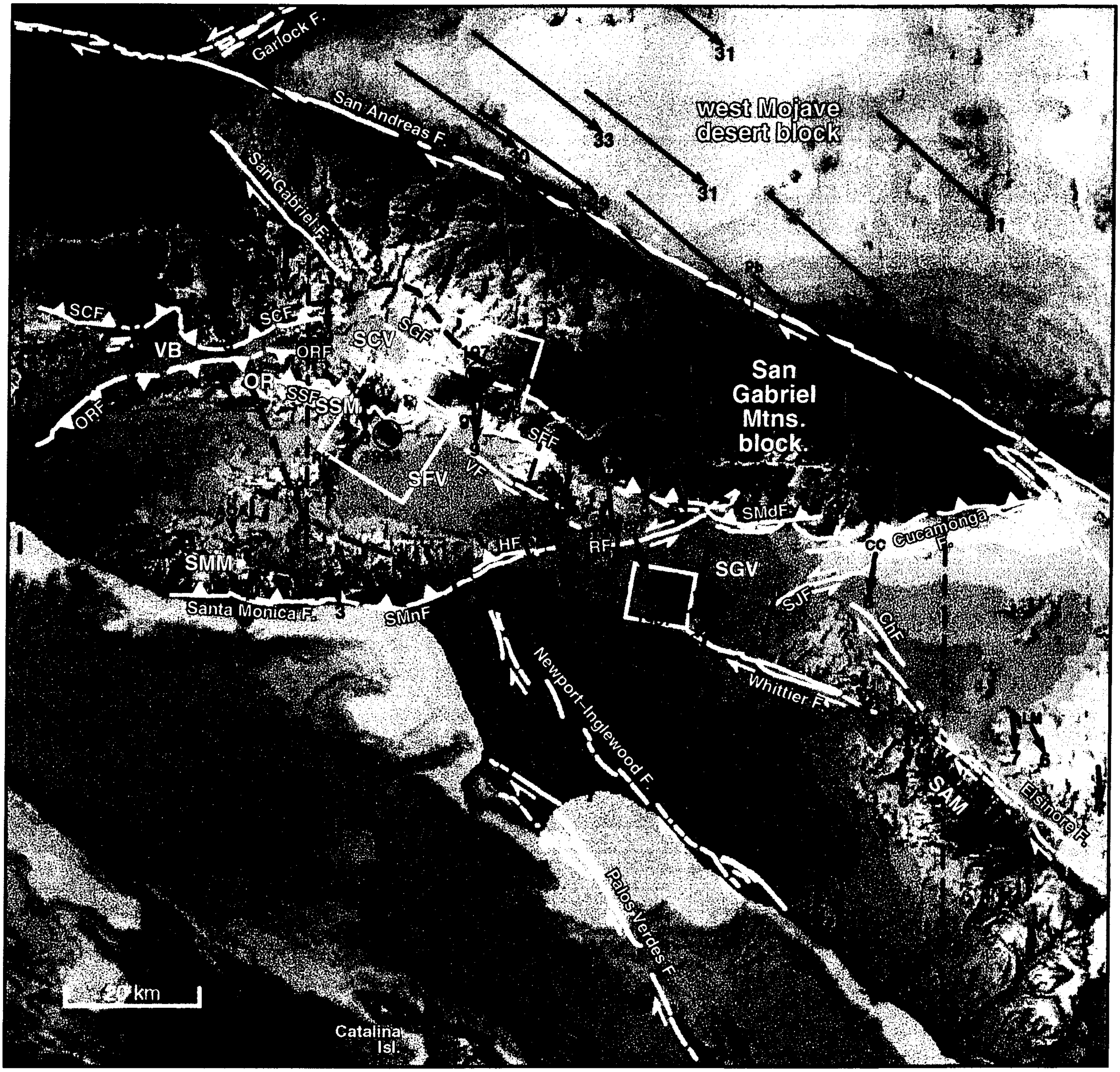
Northridge, (Dm1) Pacoima Dam 1, (Hr) Hopper, (JPL) Jet Propulsion Lab, (LM) Lake Mathews, (LV) Loma Verde, (LY) Longdon Yard, (ML) Mount Lee, (MW) Mount Wilson, (OM) Oat Mountain, (Rk) Rocketdyne, (SdP) Saddle Peak, (SJ) San Juan, (SP) Santa Paula, (SP2) Santa Paula 2, (ST) San Tuze, (Tr) Tracker, (UCLA) University of California at Los Angeles, (USC) University of Southern California, (WC) Whittier College, and (WH) Work Hill. Abbreviations at geodolite sites are omitted. Fault and place abbreviations are: (ChF) Chino Fault, (HF) Hollywood Fault, (OR) Oak Ridge, (ORF) Oak Ridge Fault, (RF) Raymond Fault, (SAM) Santa Ana Mountains, (SCF) San Cayetano Fault, (SFV) San Fernando Valley, (SGF) San Gabriel Fault, (SGV) San Gabriel Valley, (SJF) San Jose Fault, (SCV) Santa Clarita Valley, (SMnF) Santa Monica Fault, (SMM) Santa Monica Mountains, (SSF) Santa Susana Fault, (SSM) Santa Susana Mountains, (SMdF) Sierra Madre Fault, and (VB) Ventura Basin.

Figure 2. The south component of sites velocities are plotted along four north-south profiles. The elastic strain due to locking of the the San Andreas and San Jacinto faults has been removed. Error bars are standard errors. The magenta line segments mark where the gradient in the south velocity component is largest; the endpoints of the magenta line segments correspond roughly to the limits of the shortening belt delineated in Figure 1. The Pasadena-downtown profile shows that shortening at ~6 mm/yr is being taken up between USC and JPL.

Figure 3. The west component of the velocities of all but the island sites are plotted. The elastic strain due to locking of the the San Andreas and San Jacinto faults has been removed. Aside from San Andreas elastic strain east-west lengthening across metropolitan L.A. is minor, it being 0 +-2.5 mm/yr (magenta line), less than the 6 mm/yr estimated by Walls et al. (1998) (blue line) with no correction for elastic strain due to locking of the San Andreas fault.

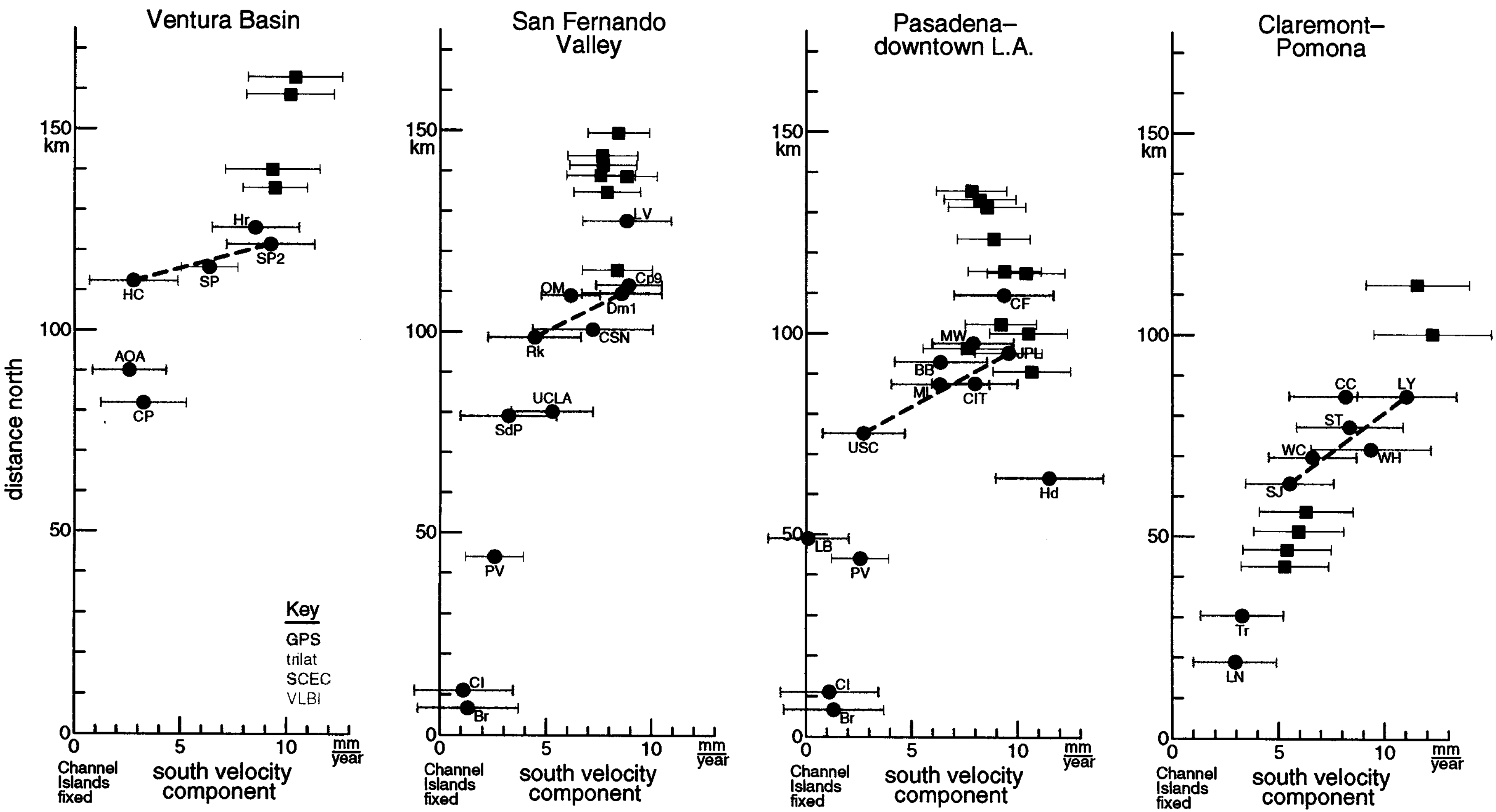
velocity field after removing the elastic strain due to locking of the San Andreas

Channel Islands fixed



Mojave segment, San Andreas F.
deep slip rate= 25 mm/yr
locking depth= 20 km

Figure 1


Ventura Basin
San Fernando Valley
Pasadena–downtown L.A.
Claremont–Pomona
distance north
150 km
100
50
0
5
10
mm/year
Channel Islands fixed
south velocity component
Hr
SP2
SP
HC
AOA
CP
LV
Cp9
OM
Dm1
Rk
CSN
UCLA
SdP
PV
CI
Br
CF
MW
JPL
BB
ML
CIT
USC
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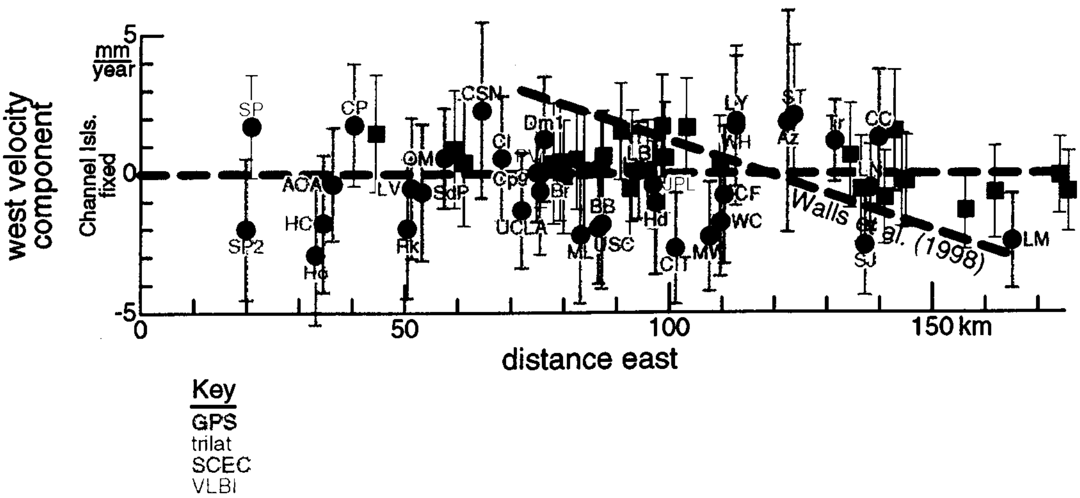
Key
GPS
trilat
SCEC
VLBI

Figure 2



west velocity component
Channel Isls. fixed
mm/year
5
0
-5
0
50
100
150 km
distance east
Walls et al. (1998)
Key
GPS
trilat
SCEC
VLBI

Figure 3